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# THE FORM FACTOR RATIO $G_{E_n}/G_{E_p}$ AT LOW MOMENTUM TRANSFERS*

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## ABSTRACT

Measurements of the ratio of the deuteron-to-proton electric form factors, $G_{E_d}/G_{E_p}$, were made from elastic electron-deuteron scattering to a precision of approximately 1% for the range of momentum transfers, $0.10 \leq q^2 \leq 0.8\ f^{-2}$, and for electron scattering angles of $45^\circ$ to $120^\circ$. It was found that within experimental errors the slope as obtained from the ratio $G_{E_n}/G_{E_p}$ agrees with the extrapolated thermal neutron-electron interaction slope when relativistic corrections and Feshbach-Lomon deuteron wave functions are applied to the electron-deuteron scattering results. The deuteron radius was found to be $1.95 \pm 0.02$ f, which agrees with the radius predicted by the Feshbach-Lomon calculation.

* * *

We have measured the ratio of elastic electron-deuteron scattering to elastic electron-proton scattering in the range of momentum transfers $0.1 \leq q^2 \leq 0.8\ f^{-2}$ with a precision of one percent or better.

It is possible to extract from such measurements values for the ratio $G_{E_n}/G_{E_p}$. In our range of momentum transfers this ratio is very close to the value of $G_{E_n}$. The proton charge form factor $G_{E_p}$ has not been extensively measured at such low values of $q^2$ and the use of experimental fits to data at higher momentum transfers to extract $G_{E_n}$ must be made with the assumption that there are no unusual fluctuations in this region. We report the ratio $G_{E_n}/G_{E_p}$ and apply the best known fits of $G_{E_p}$ to extract a value of $G_{E_n}$.

Few, but precise, data have been reported in our range of momentum transfers.[1] This work has been done to look more accurately at the discrepancy between the results of neutron-electron interaction measurements,[2] which yield a positive slope $dG_{E_n}/dq^2$ at $q^2 = 0$, and the fact that the value and the slope of $G_{E_n}$ as extracted from electron-deuteron scattering averaged to zero at all values of $q^2$. This apparent disagreement was not removed by previous measurements at low momentum transfers.[1]

The extraction of $G_{E_n}$ from electron-deuteron scattering data requires knowledge about the deuteron wave functions. Major efforts have been made in the last ten years (see, e.g., Refs. 3, 4, and 5) to improve the status of the theory of the deuteron. Gross[6] has shown that relativistic corrections to the wave functions, although small in the range of $q^2$ considered here, can play a very important role in the extraction of $G_{E_n}$. Casper and Gross[7] found that with the proper choice of realistic wave functions and the application of relativistic corrections it was possible to affect the data in a direction that would tend to reduce the difference between the neutron-electron interaction results and those from electron-deuteron scattering.

The experiments were performed at the linear accelerator of the Naval Postgraduate School at Monterey in the range $0.1 \leq q^2 \leq 0.4\ f^{-2}$ and at the Mark III accelerator at Stanford University in the range $0.2 \leq q^2 \leq 0.8\ f^{-2}$. The experimental set-up was basically the same in both laboratories.

A well-defined beam of electrons with a momentum spread of $\leq 0.1\%$ passed through the targets and then into a beam collector. The targets used were polyethylene $(CH_2)n$ and deuterated polyethylene $(CD_2)n$. A carbon target was used for background subtraction. The target thicknesses ($< 10^{-3}$ rad. lengths) were matched for equal energy loss by ionization to optimize the conditions for the carbon subtractions. The normalization factor for this subtraction was obtained by measuring the number of counts under the carbon peaks in the three targets at the various energies and angles. The scattered electrons were analyzed in momentum in a magnetic spectrometer and counted in a multichannel array of scintillator counters. The relative efficiencies of the counters were separately determined before each set of data points.

The absolute energy of the incoming electrons was known to $\approx 0.2\%$ and monitored by nuclear magnetic resonance. The spectrometers were monitored and stabilized by accurate rotating coil fluxmeters.

The scattering angle at the Stanford laboratory has been determined to $0.05^{\circ}$ and to $0.1^{\circ}$ at the Monterey laboratory. It is clear that many parameters that would influence an absolute measurement cancel out in a ratio determination, e.g., solid angle, charge integration, absolute counter efficiency, etc. To this end we have kept the scattering angle, solid angle and scattered momentum fixed for the carbon, $CH_2$ and $CD_2$ measurements at each data point. The incident energy was adjusted to give the correct $q^2$. Only small changes in energy were necessary, as shown in Table I.

Radiative corrections were calculated according to Tsai.[8] Because of a possible contribution by quasi-elastically scattered electrons from the deuteron, cut-offs on the radiative tails of the deuteron and the proton peaks were made at energies less than 2.2 MeV below the peak. We have shown that the ratios formed from our data are independent of the cut-off position in the radiative tail.

The deuteron form factor $G_D$ is determined experimentally by

$$\left(\frac{d\sigma}{d\Omega}\right)_{Exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times G_D^2 \quad . \tag{1}$$

$G_D^2$ can be brought into the form[6]

$$G_D^2 = A(q^2) + B(q^2) \tan^2 \theta/2 \; . \tag{2}$$

With $\eta = \frac{q^2}{4M_d^2} \ll 1$ in our range and making $1 + \eta \rightarrow 1$ , we have

$$A(q^2) = G_C^2 + \frac{8}{9} \eta^2 G_Q^2 + \frac{2}{3} \eta G_M^2 \quad \text{and} \quad B(q^2) = \frac{4}{3} \eta G_M^2 \; . \tag{3}$$

$G_C$ , $G_Q$ , and $G_M$ stand for the physical charge, quadrupole, and magnetic form factors of the deuteron, respectively. They are connected to the physical nucleon-electric form factors for the proton and neutron ($G_{E_p}$ and $G_{E_n}$ , respectively) by

$$G_C = (G_{E_p} + G_{E_n}) D_c \tag{4}$$

$$G_Q = (G_{E_p} + G_{E_n}) D_Q$$

$$G_M = (G_{E_p} + G_{E_n}) D_M^E + (G_{M_p} + G_{M_n}) D_M^M \; .$$

The $D_c$ , $D_Q$ , $D_M^E$ , and $D_M^M$ are integrals over suitably chosen wave-functions of the deuteron. The model dependence of our result is contained in these terms.

In the kinematic range of this experiment, $G_{M_d} = \mu_d E_d$ is a good approximation. The expression for $G_M$ is considerably simplified when this is assumed, as well as "scaling" for the proton and neutron; i.e., $G_{M_p} = \mu_p G_{E_p}$ and $G_{M_n} = \mu_n G_{E_p}$ . (The μ's are the magnetic moments of the respective particles.)

The results of the Drickey and Hand[1] experiment directly support this assumption in the momentum transfer range of our experiment. They find $G_{E_p} = G_{M_p}/\mu_p = 1.008 \pm .014$ . In the deuteron, our maximum magnetic correction is $< 1\%$ , so that a 1% violation of scaling has a negligible effect on our results.

Making use of scaling, we have

$$G_M = (G_{E_p} + G_{E_n})\,\mu_d D_c \quad , \tag{5}$$

and finally

$$G_D^2 = (G_{E_p} + G_{E_n})^2 \left[ D_c^2 \left(1 + \frac{2}{3}\,\eta\,\mu_d^2\,(1 + 2\tan^2\theta/2)\right) + \frac{8}{9}\,\eta^2 D_Q^2 \right] . \tag{6}$$

The contribution of the quantity $\frac{8}{9}\,\eta^2 D_Q^2$ within the brackets is about $5 \times 10^{-4}$ at our highest value of $q^2$ . It has been neglected. The term $\frac{2}{3}\,\eta\,\mu_d^2\,(1 + 2\tan^2\theta/2)$ represents the magnetic contribution to $G_D^2$ . When it is factored out of the data we are left with

$$G_{E_d} = (G_{E_p} + G_{E_n}) D_c \tag{7}$$

Dividing the proton data by the analagous magnetic factor, the ratio measurement of the elastic proton and deuteron scattering is reduced to $G_{E_d}/G_{E_p}$ . The ratio of $G_{E_n}/G_{E_p}$ is extracted from

$$\frac{G_{E_n}}{G_{E_p}} = \frac{1}{D_c} \frac{G_{E_d}}{G_{E_p}} - 1 . \tag{8}$$

In our range of momentum transfers, the quantities $D_c$ and $G_{E_p}$ are close to one, so that a small change in either of them has a strong influence on $G_{E_n}$ .

Much of the earlier experimental work on elastic electron-deuteron scattering has been analyzed with wave functions developed by Partovi[9] from a Hamada potential with a core radius of 0.485 F and a D-state contribution of 7%.

Feshbach and Lomon[10] proposed a deuteron boundary-condition model with a core radius of 0.735 F and a D-state value equal to 4.9%. (Within the limits from 4.6% and 6.1% their values of $D_c$ vary only by about 1 part in $10^{-3}$ in our range of momentum transfer.)

Many attempts have been made to derive a relativistic theory for elastic electron-deuteron scattering. Gross[6] made the most complete attempt to find relativistic effects by treating the deuteron wave function in a relativistic manner. These calculations describe the distortion of the wave function of a moving deuteron. Corrections stemming from relativistic modifications of the nucleon current seem to be small and are neglected. Casper and Gross[7] derived a relativistic treatment of the wave function that yields an additive correction, $\Delta G_{E_n}$ , to $G_{E_n}$ . Such a correction is approximately equal to $q^2/8M_p^2$ and it is reasonably model independent. They also showed that meson exchange effects give negligible contributions below $q^2 \approx 10\ f^{-2}$ .

The Partovi (P) and the Feshbach-Lomon (FL) models with and without relativistic corrections are applied to our data in the next section.

In Table I we present our experimental data. The error quoted consists of counting errors (including the carbon subtraction and efficiency corrections) and an error of 0.5% in the target thickness determination.

Table II shows four sets of values of $G_{E_n}/G_{E_p}$ as obtained with

(a) the Feshbach-Lomon wave function with relativistic corrections,

(b) the Feshbach-Lomon wave function without relativistic corrections,

(c) the Partovi wave function with relativistic corrections, and

(d) the Partovi wave function without relativistic corrections.

Values for the relativistic correction $\Delta G_{E_n}$ and the structure factor $D_c$ for the Feshbach-Lomon wave function are also given.

In each of the columns we show the slope $d(G_{E_n} / G_{E_p})/dq^2$ to illustrate the rapid decrease in the slope when going from a relativistically corrected Feshbach-Lomon wave function to an uncorrected Partovi wave function. These fits assumed a value of zero for the intercept. (We are aware of the slight inconsistancy in adding $\Delta G_{E_n}$ to the ratio $G_{E_n}/G_{E_p}$.)

In order to extract values of $G_{E_n}$ we have used the deVries b' fit[11] for the proton form factor $G_{E_p}$. This fit is in very good agreement with the absolute measurements of $G_{E_p}$ that were made by Drickey and Hand. Table III shows the results of this application for the two extreme cases presented in Table II. The slopes as determined by the two evaluations are also given for comparison with the neutron-electron interaction slope. The errors are weighted by the $\chi^2$ of the fit.

It is interesting to note that if a non-zero intercept were assumed, then our results still yield a consistent value of the slope. In such a case we find the slope = 0.022 ± 0.008 and the intercept is

$-0.002 \pm 0.003$ for the data evaluated with the Feshbach-Lomon wave function and the relativistic correction.

We can use our measurements of $G_{E_d}/G_{E_p}$ to extract a value of the deuteron radius, $r_d$. However, an expansion of the structure function, $D_c$, becomes model dependent for values of $q^2$ as low as $0.1\ f^{-2}$. In the expansion

$$D_c = 1 - \frac{q^2 < r_d^2 >}{6} + \lambda q^4 \qquad (9)$$

the value of $\lambda$ from the Feshbach-Lomon calculation is 0.3 in the range $.1 \leq q^2 \leq .3$.[12] Expanding Eq. 7 and including Eq. 9, we have

$$G_{E_d}/G_{E_p} \approx 1 - \frac{q^2}{6}\left(< r_d^2 > - < r_n^2 >\right) + \lambda q^4 . \qquad (10)$$

$< r_n^2 > = 0.116\ f$ and is obtained from the neutron-electron slope.

The best fit to our data points to Eq. 10 up to $q^2 = 0.4\ f^{-2}$ yields $r_d = 1.95 \pm .02\ f$. A change of $\lambda$ by $\pm .05$ changes the deuteron's radius by one standard deviation. A good fit to our data requires the $q^4$ term. Higher order terms in $D_c$ might be important beyond this value of $q^2$. The Feshbach-Lomon calculation gives $r_d = 1.94\ f$.

In Fig. 1 we present the contents of Table III. The three points of Drickey and Hand (as re-evaluated by Buchanan[13]) that fall in our range of $q^2$ are also plotted.

Barring unexpected fluctuations of $G_{E_p}$ in our range of momentum transfers, we conclude:

(a) When the Feshbach-Lomon wave function together with relativistic corrections is applied to the data, one finds agreement between the neutron-electron slope at $q^2 \approx 0$ and the slope given by values of $G_{E_n}$ in the range $0.10 \leq q^2 \leq 0.80$.

(b) Even within the relatively large errors propagated into $G_{E_n}$, the Partovi wave function with relativistic corrections yields a slope that is in disagreement with the neutron-electron interaction slope.

(c) There is agreement within errors between the deuteron radius from experiment and that obtained from the Feshbach-Lomon wave function that was used in (a) to find the slope of $G_{E_n}$.

We wish to thank the many people who have helped us to make this experiment possible. Professor R. Hofstadter has given us support and the free use of the Mark III accelerator at Stanford University. Mrs. Nancy Spencer has computed the Feshbach-Lomon wave functions from a program supplied by Professor E. Lomon. Professors J. Friedman and R. Blankenbecler gave useful advice and comments.

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## TABLE CAPTIONS

Table I Summary of experimental data. Columns 1, 2, 3, and 4 contain the momentum transfer, scattering angle and incident electron energies for the proton and deuteron data points, respectively. Columns 5 and 6 are explained in Note b. Column 7 has the measured ratios of deuteron electric form factor to proton electric form factor. Column 8 is the total experimental error for each point and Column 9 is the weighted average plus errors for the points at each value of momentum transfer.

Table II Column 1 is the momentum transfer. Column 2 is the relativistic correction to $G_{E_n}$ as calculated by Gross. $D_c^{FL}$ in Column 3 is the deuteron structure function as calculated by Feshbach-Lomon. The succeeding columns are the results for $G_{E_n}/G_{E_p}$ using relativistic corrections or not and Feshbach-Lomon (FL) or Partovi (P) structure functions for the deuteron. The boxes at the bottom give the slope of the best line fit to $G_{E_n}/G_{E_p}$ for the different cases.

Table III The de Vries b' fit is used to find $G_{E_n}$ for three of the cases shown in Table II. Column 2 gives the value of $G_{E_p}$ used.

Table I

MEASURED RATIO OF $G_{E_d}/G_{E_p}$

| $q^2$ ($f^{-2}$) | $\theta$ | $E_{i_p}$ [a] (MeV) | $E_{i_d}$ (MeV) | Magnetic Correction[b] proton | Magnetic Correction[b] deuteron | $G_{E_d}/G_{E_p}$ | Percent error | Weighted Average $G_{E_d}/G_{E_p}$ |
|---|---|---|---|---|---|---|---|---|
| 0.10 | 75° | 52.3 | 51.8 | 0.9828 | 0.9988 | 0.9499 | 1.14 | 0.9374 ± 0.0057 |
| | 90° | 45.2 | 44.6 | 0.9760 | 0.9984 | 0.9459 | 0.86 | |
| | 45° | 82.6 | 82.0 | 0.9897 | 0.9993 | 0.9200 | 0.91 | |
| 0.20 | 75° | 74.6 | 73.5 | 0.9661 | 0.9976 | 0.8734 | 0.71 | 0.8903 ± 0.0029 |
| | 120° | 53.1 | 52.0 | 0.8948 | 0.9925 | 0.9030 | 0.59 | |
| | 45° | 117.4 | 116.3 | 0.9796 | 0.9985 | 0.8931 | 1.54 | |
| | 45° | 117.4 | 116.3 | 0.9796 | 0.9985 | 0.9284 | 1.06 | |
| | 45° | 117.4 | 116.3 | 0.9796 | 0.9985 | 0.9144 | 1.06 | |
| | 45° | 117.4 | 116.3 | 0.9796 | 0.9985 | 0.8677 | 0.81 | |
| | 45° | 117.4 | 116.3 | 0.9796 | 0.9985 | 0.8737 | 0.81 | |
| 0.30 | 45° | 144.3 | 142.8 | 0.9697 | 0.9978 | 0.8275 | 0.79 | 0.8392 ± 0.0031 |
| | 75° | 91.9 | 90.3 | 0.9500 | 0.9965 | 0.8317 | 0.99 | |
| | 90° | 79.6 | 78.0 | 0.9313 | 0.9951 | 0.8462 | 0.61 | |
| | 105° | 71.3 | 69.7 | 0.9014 | 0.9929 | 0.8424 | 0.64 | |
| 0.40 | 90° | 92.5 | 90.3 | 0.9106 | 0.9935 | 0.7984 | 0.62 | 0.8041 ± 0.0031 |
| | 45° | 167.2 | 165.1 | 0.9601 | 0.9971 | 0.8153 | 0.88 | |
| | 45° | 167.2 | 165.1 | 0.9601 | 0.9971 | 0.7945 | 0.89 | |
| | 45° | 167.2 | 165.1 | 0.9601 | 0.9971 | 0.8114 | 0.75 | |
| 0.50 | 60° | 144.8 | 142.1 | 0.9383 | 0.9955 | 0.7626 | 0.79 | 0.7626 ± 0.0061 |
| 0.60 | 60° | 159.2 | 156.0 | 0.9270 | 0.9946 | 0.7260 | 0.71 | 0.7260 ± 0.0052 |
| 0.80 | 75° | 153.5 | 149.2 | 0.8772 | 0.9906 | 0.6707 | 0.97 | 0.6744 ± 0.0044 |
| | 75° | 153.5 | 149.2 | 0.8772 | 0.9906 | 0.6773 | 0.85 | |

a: Measurements above 100 MeV have been made at the Stanford Mark III accelerator.

b: The magnetic correction gives the number by which the experimental $G_p^2$ or $G_D^2$ has been multiplied to remove the magnetic contributions to $G_{E_p}^2$ or $G_{E_d}^2$.

Table II

VALUES FOR $G_{E_n}/G_{E_p}$

| $q^2$ $(f^{-2})$ | $\Delta G_{E_n}$ | $D_c^{FL}$ | $\left(\frac{G_{E_n}}{G_{E_p}}\right)^{FL} + \Delta G_{E_n}$ | $\left(\frac{G_{E_n}}{G_{E_p}}\right)^{FL}$ no $\Delta G_{E_n}$ | $\left(\frac{G_{E_n}}{G_{E_p}}\right)^{P} + \Delta G_{E_n}$ | $\left(\frac{G_{E_n}}{G_{E_p}}\right)^{P}$ no $\Delta G_{E_n}$ |
|---|---|---|---|---|---|---|
| 0.10 | 0.0006 | 0.9398 | -0.0020 ± 0.0055 | -0.0026 ± 0.0055 | -0.0034 ± 0.0055 | -0.0040 ± 0.0055 |
| 0.20 | 0.0012 | 0.8867 | +0.0052 ± 0.0032 | +0.0040 ± 0.0032 | +0.0030 ± 0.0032 | +0.0018 ± 0.0032 |
| 0.30 | 0.0018 | 0.8397 | +0.0012 ± 0.0036 | -0.0006 ± 0.0036 | -0.0020 ± 0.0036 | -0.0038 ± 0.0036 |
| 0.40 | 0.0024 | 0.7976 | +0.0105 ± 0.0038 | +0.0081 ± 0.0038 | +0.0062 ± 0.0038 | +0.0038 ± 0.0038 |
| 0.50 | 0.0030 | 0.7596 | +0.0069 ± 0.0079 | +0.0039 ± 0.0079 | +0.0014 ± 0.0079 | -0.0016 ± 0.0079 |
| 0.60 | 0.0036 | 0.7251 | +0.0048 ± 0.0071 | +0.0012 ± 0.0071 | -0.0009 ± 0.0071 | -0.0045 ± 0.0071 |
| 0.80 | 0.0048 | 0.6645 | +0.0197 ± 0.0065 | +0.0149 ± 0.0065 | +0.0131 ± 0.0065 | +0.0083 ± 0.0065 |
| Straight line slope (with zero intercept): | | | +0.0185 ± 0.0038 | +0.0125 ± 0.0038 | +0.0087 ± 0.0040 | +0.0027 ± 0.0040 |

Table III

EXTRACTED SLOPES $dG_{E_n}/dq^2$

| $q^2$ $(f^{-2})$ | $G_{E_p}$[a] deVries b' fit | $G_{E_n}$ FL | $G_{E_n} + \Delta G_{E_n}$ FL | $G_{E_n}$ P |
|---|---|---|---|---|
| 0.10 | 0.9881 | -0.0026 | -0.0020 ± 0.0054 | -0.0038 ± 0.0054 |
| 0.20 | 0.9765 | +0.0039 | +0.0051 ± 0.0031 | +0.0017 ± 0.0031 |
| 0.30 | 0.9652 | -0.0006 | +0.0012 ± 0.0035 | -0.0037 ± 0.0035 |
| 0.40 | 0.9540 | +0.0077 | +0.0101 ± 0.0036 | +0.0036 ± 0.0036 |
| 0.50 | 0.9431 | +0.0037 | +0.0067 ± 0.0074 | -0.0015 ± 0.0074 |
| 0.60 | 0.9321 | +0.0011 | +0.0047 ± 0.0066 | -0.0042 ± 0.0066 |
| 0.80 | 0.9115 | +0.0136 | +0.0184 ± 0.0059 | +0.0076 ± 0.0059 |
| Straight line slope (with zero intercept): | | | +0.0179 ± 0.0036 | +0.0036 ± 0.0036 |

Slope n - e interaction: 0.0195 ± 0.0004

a: No error has been applied to $G_{E_p}$ .

## FIGURE CAPTION

Figure 1 Straight line fit to values of $G_{E_n}$ as extracted from the data with the deVries b' fit. Curve 1 is the extrapolated neutron-electron interaction slope. Curve 2 is the fit to the points indicated by ●. These points are $G_{E_n} + \Delta G_{E_n}$, where $G_{E_n}$ is calculated from the data using the Feshbach-Lomon wave functions and $\Delta G_{E_n}$ are the relativistic corrections of Gross.[6] Curve 3 is fitted to the points shown by $\Delta$. The Partovi wave function was used to extract $G_{E_n}$ from these data. The points plotted with × are from Drickey and Hand,[1,13] calculated from their data in the same way as those of curve 2.

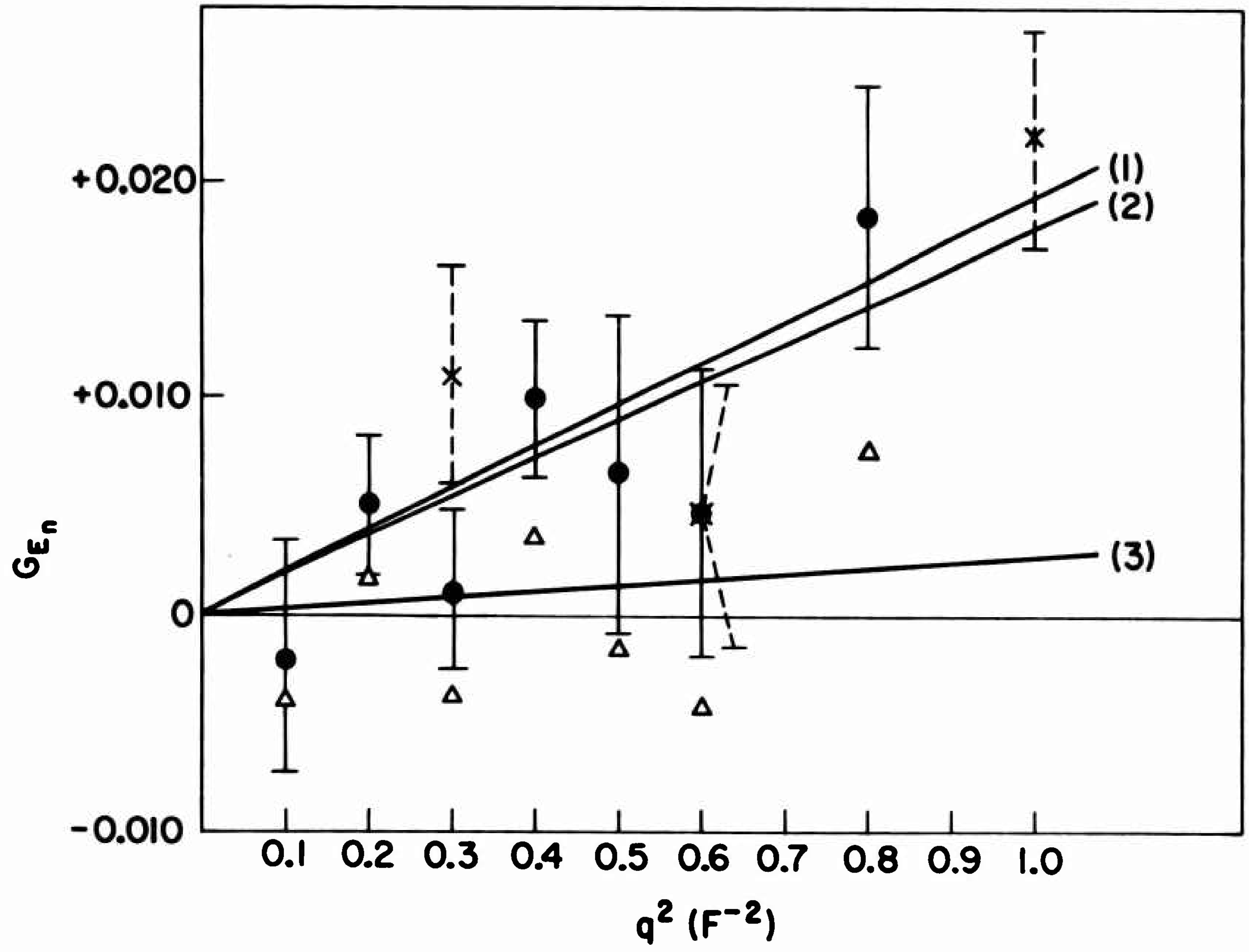


Figure 1

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13. ABSTRACT

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